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IEEE Recommended Practice for Performing Temperature Rise Tests on Oil-Immersed Power Transformers at Loads Beyond Nameplate Ratings

Power Engineering Society

Sponsored by the
Transformers Committee

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Abstract: Recommendations are made, where possible, regarding the performance and evaluation of temperature rise tests on oil-immersed power transformers beyond nameplate ratings. The intent is to assist power transformer manufacturers, and the ultimate users, in evaluating thermal performance of the transformers under varying loads.
Keywords: bottom oil temperature, conditioning loads, hottest spot factor, loading, load tap changer, mineral-oil-immersed, power transformers, rated load, thermal capacity, top oil temperature

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Introduction

(This introduction is not a part of IEEE Std C57.119-2001™, IEEE Recommended Practice for Performing Temperature Rise Tests on Oil-Immersed Power Transformers at Loads Beyond Nameplate Ratings.)

This introduction provides background related to the development of this recommended procedure. Additional information may be found in Annex B.

Over the years, there has been a marked increase in the practice of loading transformers beyond their nameplate rating. In the past, many transformers were loaded beyond nameplate rating only during short time emergencies. Today, many users have established loading practices which subject transformers to loads beyond nameplate rating on a planned basis during periods of seasonal or daily peak loads, in addition to unexpected loads occurring during short or long time emergencies.

Former ANSI loading guide C57.91 provided loading guidelines for distribution transformers, ANSI C57.92 provided loading guidelines for power transformers rated 100 MVA and below, and IEEE Std C57.115™ provided loading guidelines for transformers rated above 100 MVA. All of these documents have been combined into a revised IEEE Std C57.91™. These documents provide transformer loading guidelines based on judgment gained from years of experience of loading transformers. However, prior to this document, no standard test procedure existed to evaluate the consequences of loading a transformer at loads beyond nameplate rating.

Investigations carried out in the past by transformer users raised concern about the accuracy of the equations and empirical constants used in the transient loading equations of these loading guides. Their experience with monitoring operating transformers indicated that transformers could carry loads greater than nameplate rating, without apparent damage. Also, there has been concern that ancillary equipment, such as tap changers, bushings, and instrumentation may not have the same overload capabilities as the core and coil assembly.

The above conditions and concerns led to a desire for a test procedure that would:

a) Provide data on the thermal characteristics of oil-immersed transformers to be used to evaluate the accuracy of the equations and empirical constants used in the loading equations in the oil-immersed transformer loading guides.
b) Demonstrate that a transformer may be loaded with a specified sequence of loads, including loads beyond nameplate rating, without exceeding those temperatures specified or agreed upon by the user and manufacturer.
c) Demonstrate that the ancillary equipment on an oil-immersed transformer would not impose limitations on those loading conditions recommended in the loading guides.

This guide describes three test procedures. Clause 9 describes a test procedure for determining the thermal characteristics of an oil immersed power transformer. Clause 10 describes a test procedure for performing load cycle temperature rise tests to assess the capability of a transformer to be loaded with a specific load cycle. Clause 11 describes a recommended integrated procedure for determining thermal characteristics and performing a load cycle temperature rise test.

It is anticipated that data obtained from tests performed in accordance with these procedures will be collected and analyzed by a future IEEE Working Group to establish a database that can be utilized to improve the accuracy of the assumptions and equations used in future loading guides.

References to other standards have been updated where applicable and all units of measurements are specified in metric units only, wherever practical

All cooling class designations have been replaced with new cooling class designations per Table 2 of IEEE Std C57.12.00-2000™.

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Contents

IEEE Recommended Practice for Performing Temperature Rise Tests on Oil-Immersed Power Transformers at Loads Beyond Nameplate Ratings

1. Overview

This document consists of three recommended test procedures, each to determine or verify transformer thermal capabilities for different purposes. Clause 1 through Clause 8 include information applicable to all three test procedures. Clause 9 is a recommended test procedure for determining the thermal characteristics of an oil-immersed power transformer from data obtained from three temperature rise tests at three specified loads. Clause 10 is a recommended procedure for performing a temperature rise test while applying a varying load, conforming to a specified loading profile, to verify that specified transformer temperatures do not exceed guaranteed values when the transformer is loaded to the specified loading profile. Clause 11 is a recommended procedure, combining the procedures in Clause 9 and Clause 10, with the objective of achieving the purpose of both clauses with reduced test time. Clause 11 is similar to Clause 10, except that the three loads are selected to simulate the temperatures expected to occur during a specific load cycle. Each of the procedures may be performed independent of the other. However, it is recommended that tests per Clause 9 be performed before Clause 10, if both tests are to be performed.

1.1 Scope

This recommended practice covers temperature rise test procedures for determining those thermal characteristics of power transformers needed to appraise the transformer's load carrying capabilities at specific loading conditions other than rated load.

1.2 Purpose

These recommended test procedures for performing temperature rise tests on power transformers are for the purpose of

a) Determining the thermal characteristics of a transformer needed to appraise the thermal performance of a transformer at loads other than nameplate rating

b) Verifying that a transformer can be loaded with a specified load profile without exceeding specified temperature rise

c) Assessing a transformer's performance during transient loading, simulating a load cycle that includes loads in excess of nameplate rating

Tests performed in accordance with Clause 9 are for the purpose of determining transformer thermal characteristics in a consistent manner. Data may then be accumulated from a large number of transformers and used to evaluate the accuracy of the equations and the empirical constants used in the loading guides.

Tests performed in accordance with Clause 10 are for the purpose of demonstrating the thermal effects of loading a transformer with a specified sequence of loads, including loads beyond nameplate rating.

Tests performed in accordance with Clause 11 are for the combined purposes of determining the thermal characteristics of a transformer and demonstrating the thermal effects of loading with a designated load cycle. This is accomplished by performing temperature rise tests at three loads, similar to Clause 9, except the three loads are selected to simulate the thermal effects of a specific load cycle.

It is not intended that all of these procedures be performed on a transformer design. It is intended that only one of the following combination of test procedures be specified:

a) Clause 9 only, when thermal characteristics are to be determined.
b) Clause 10 only, when only verification of complying with temperatures limits when loaded to a specific load profile is needed.
c) Clause 9 plus Clause 10, when both thermal characteristics and verification of compliance with temperature limits when loaded to a specific load profile are needed.
d) Clause 11 when both thermal characteristics and verification of compliance with temperature limits when loaded to a specific load profile are required, and the load profile can be represented with three steady state loads.

The user should specify which of the test procedures are required at the time of specification.

A further purpose of these procedures is to obtain information with respect to possible loading limitations imposed on the transformer by oil levels and ancillary equipment when the transformer is operated at loads beyond nameplate rating.

2. References

This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

ANSI C57.12.10-1997, American National Standard for Transformers 230 kV and Below 833/958 through 8333/10 417 kVA, Single-Phase, and 750/862 through 60 000/80 000/100 000 kVA, Three-Phase without Load Tap Changing; and 3750/4687 through 60 000/80 000/100 000 kVA with Load Tap Changing—Safety Requirements.[1]

IEEE PC57.130™/D13, Draft Guide for the Detection and Identification of Gases Generated in Oil Immersed Transformers During Factory Tests.[2]

[1]ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[2]This IEEE standards project was not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining a draft, contact the IEEE.

IEEE Std C57.12.00-2000™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.[3]

IEEE Std C57.12.80-1978™ (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90-1999™, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers.

IEEE Std C57.91-1995™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

IEEE Std C57.104-1991™, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.

NOTE—At the time this guide was approved, IEEE PC57.130, Draft Guide for Gas Analysis During Factory Tests was in the development process. When issued, it should be used as a reference instead of IEEE Std C57.104-1991™.

3. Definitions and symbols

3.1 Definitions

For the purposes of this recommended practice, the following terms and definitions apply. Unless otherwise specified, transformer-related terms are defined in IEEE C57.12.80-1978™.[4] *The Authoritative Dictionary of IEEE Standards Terms* [B10][5] should be referenced for terms not defined in this clause.

3.1.1 average winding temperature: The average temperature of the hottest winding as determined from the ohmic resistance measured across the terminals of the winding in accordance with the cooling curve procedure specified in IEEE Std C57.12.90-1999™.

3.1.2 average winding temperature rise: The arithmetic difference between the average winding temperature and the average temperature of the air surrounding the transformer.

3.1.3 directed flow (oil-immersed forced oil cooled transformers): This indicates that the principal part of the pumped oil from heat exchangers or radiators is forced, or directed, to flow through specific paths in the winding.

3.1.4 equilibrium temperature: A temperature of a measured quantity that does not vary by more than 2.5% or 1 ˚C, whichever is greater, during a consecutive 3-hour period.

3.1.5 exponent *m*: One-half of the exponential power of per unit load current K versus winding temperature rise.

NOTE—This definition of m is not in strict accordance with the definition in previous loading guides IEEE Std C57.92-1981™ and IEEE Std C57.115-1991™. These loading guides defined the exponent m as a function of losses but used it as an exponent of the load [see Annex A, Equation (A.2)]. The definition above is in accordance with the use of the exponent in the equations in these documents and with the definition in IEEE Std C57.91-1995™.

3.1.6 exponent *n*: The exponential power of $(K^2R + 1)/(R + 1)$ versus top oil temperature rise.

[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[4]Information on references can be found in Clause 2.

[5]The numbers in brackets correspond to those of the bibliography in Annex D.

NOTE—This definition of n is not in strict accordance with previous loading guides IEEE Std C57.92-1981 or IEEE Std C57.115-1991™. These loading guides defined n as an exponent of the total loss versus top oil temperature rise. However, the loading guides calculate the ultimate top oil temperature rise at any per unit load K using a function of load, $(K^2R + 1)/(R + 1)$, to estimate the total losses. Because of assumptions made to simplify this loss function, the exponent obtained experimentally from a plot of measured losses versus temperature rise may be different than an exponent determined as a function of $(K^2R + 1)/(R + 1)$. In this procedure, n is defined and experimentally determined as a function of $(K^2R + 1)/(R + 1)$ rather than the losses, to be consistent with its use in the equations in the previous loading guides and with IEEE Std C57.91-1995™.

3.1.7 heat exchanger: An oil-to-air, or oil-to-water, heat exchanging device attached to an oil-filled transformer for the purpose of exchanging heat from the transformer oil to the ambient media, typically requiring pumps for oil circulation and fans for circulation of the ambient air across the heat exchanging surfaces.

3.1.8 hottest spot temperature: The maximum temperature of the surface of any current-carrying conductor in contact with oil or insulation. *See also:* **winding hottest spot temperature**.

3.1.9 nondirected flow (oil-immersed forced oil cooled transformers): This indicates that the pumped oil from heat exchangers or radiators flows freely inside the tank, and it is not forced to flow through the winding.

3.1.10 oil-immersed transformer: A transformer in which the core and coils are immersed in an insulation oil.

3.1.11 radiator: An oil-to-air heat exchanging device attached to a transformer for the purpose of exchanging sufficient heat from the transformer oil to the ambient air by natural convection of oil and air to comply with the ONAN rating temperature rise requirements. Additional heat may be exchanged by the addition of forced circulation of the ambient air or oil.

3.1.12 transformer: An oil-immersed power transformer rated in accordance with IEEE Std C57.12.00-2000™ and ANSI C57.12.10-1997.

3.1.13 top oil temperature: The temperature measured below the top surface of the oil in a transformer in a location to represent the average temperature of the topmost layer of oil in the transformer. It is the temperature of the mixed oil that has circulated across the various heated surfaces inside the transformer and risen toward the top surface.

3.1.14 winding hottest spot temperature: The maximum temperature of the surface of any winding conductor in contact with insulation or oil.

3.2 Symbols

Symbols listed is this clause and used in equations throughout this document have been selected in accordance with standard symbols adopted by the IEEE Transformers Committee, October 1988. Additional symbols, when required, were assigned following the style of the adopted symbols.

Users of this procedure are cautioned that some of these symbols may be different from those used in the referenced loading guides, which do not use symbols consistently. These loading guide equations have been rewritten in Annex A using symbols consistent with this document.

Unless otherwise expressed, all temperatures and temperature differences are in degrees Celsius, and all times and time constants are in hours.

C is the thermal capacity of transformer (watt-hours/°C). Also used as an abbreviation for degrees Celsius, as in °C.

e is the base of natural logarithm, 2.71828, (dimensionless).

F_H is the hottest spot factor (dimensionless).

IL_1, IL_2, IL_3 are the load currents corresponding to loads L_1, L_2, L_3 (A).

$n1$, I_{n2}, I_{n3}, ..I_{nj} is the incremental current added to the load current for each interval of the load cycle test (A).

I_R is the rated line current at 100% of maximum nameplate rating.

I_{T1}, I_{T2}, I_{T3} is the total current during tests simulating loads, L_1, L_2, and L_3, equal to the sum of the load current and an additional current to simulate no-load losses (A).

K is the ratio of load L to rated load (dimensionless).

K_c is the ratio of conditioning load to rated load (dimensionless).

K_{T1}, K_{T2}, K_{T3} is the ratio of per unit loads simulated by the three temperature rise tests, 9.5, 9.6, and 9.7, to the rated load (dimensionless).

K_{L1}, K_{L2}, K_{L3} is the ratio of per unit current (reduced currents) held at the ends of the tests 9.5, 9.6, and 9.7 to the rated load current (dimensionless).

L is the load under consideration in any units.

L_c is the RMS load of a 12-hour period preceding the period in the load cycle selected for the initial load (kVA).

L_R is the rated load (kVA).

L_1, L_2, L_3 are the loads simulated by temperature rise tests at reduced load (10.6), rated load (10.5), and load beyond nameplate rating (10.7) (kVA).

L_1, L_2, L_3,... L_j are the loads held during time intervals, t_1, t_2, t_3,...t_j (kVA).

m is (oil exponent) one-half the exponential power of per unit load current K versus winding temperature rise (see NOTE in 3.1.5).

n is the exponential power of $(K^2R + 1)/(R + 1)$ versus top oil temperature rise (see NOTE in 3.1.6).

ΔP is the change in total loss due to change in load current (W).

P_{NL} is the no-load loss corrected to the reference temperature specified in IEEE Std C57.12.00-2000™.

P_R is the total loss at rated load current equal to the sum of the load loss at rated current and no-load loss, both determined per IEEE Std C57.12.90-1999™ and corrected to reference temperatures as specified in IEEE Std C57.12.00-2000™.

P_{L1} , P_{L2} , P_{L3} are the total measured losses at loads L_1 , L_2 , L_3 , respectively, when temperatures have stabilized (W).

R is the ratio of load loss at rated load to no-load loss (dimensionless).

t is the duration of load (h).

t_1 , t_2 , t_3 ,... t_j are the time periods into which the load cycle is divided (h).

$\Delta\Theta_{AO,\,W}$ is the average oil temperature rise of oil in winding over ambient temperature (˚C).

$\Delta\Theta_{BO}$ is the bottom oil temperature rise over ambient temperature (˚C).

$\Delta\Theta_{H}$ is the winding hottest-spot temperature rise over top oil temperature (˚C).

$\Delta\Theta_{H,\,R}$ is the winding hottest-spot temperature rise over top oil temperature at rated load (˚C).

$\Delta\Theta_{TO,\,R}$ is the top oil temperature rise over ambient temperature at rated load (˚C).

$\Delta\Theta_{TO}$ is the top oil temperature rise over ambient temperature (˚C).

$\Delta\Theta_{TO,\,i}$ is the initial top oil temperature rise at the beginning of the load cycle (˚C) test, $t = 0$ (˚C).

$\Delta\Theta_{TO,\,1}$, $\Delta\Theta_{TO,\,2}$, $\Delta\Theta_{TO,\,3}$ is the top oil temperature rise over ambient temperature when temperatures have stabilized during loads L_1 , L_2 , L_3 , respectively (˚C).

$\Delta\Theta_{TO,\,U}$ is the ultimate top oil temperature rise for load L (˚C).

$\Delta\Theta_{TO/A}$ is the temperature rise of top oil above the ambient air temperature (˚C).

$\Delta\Theta_{W}$ is the average winding temperature rise over average oil temperature (˚C).

$\Delta\Theta_{W1}$, $\Delta\Theta_{W2}$, $\Delta\Theta_{W3}$ are the average winding temperature rises over average oil temperatures when temperatures have stabilized during loads L_1 , L_2 , L_3 , respectively (˚C).

Θ_{A} is the average temperature of the ambient air surrounding the transformer (˚C).

Θ_{H} is the temperature of the hottest spot in the transformer winding (˚C).

Θ_{TO} is the top oil temperature (˚C).

τ_{TO} is the (oil time constant) thermal time constant of the transformer top oil temperature rise for any load L and for any specific temperature differential between the ultimate top oil rise and the initial top oil rise (h).

τ_{R} is thermal time constant of transformer top oil temperature rise for rated load beginning with initial temperature rise of 0 ˚C (h).

τ_{W} is the winding time constant) thermal time constant of the average winding temperature rise above oil temperature (h).

3.2.1 Subscripts

A	ambient
c	conditioning
R	rated
U	ultimate
i	initial
H	winding hottest spot
TO	top oil
W	winding
/	over
1,2,3	Tests per 9.6, 9.5, and 9.7, respectively, or load interval in Clause 10

4. General

All temperature rise tests should be performed in accordance with procedures specified in IEEE Std C57.12.90-1999™, unless otherwise specified. The cooling curve method specified in IEEE Std C57.12.90-1999™, should be used to determine the average winding temperature rise.

4.1 Preliminary evaluation

Before these temperature rise tests are performed, the transformer design should be checked to determine if limitations other than insulation aging would limit loading of the transformer or cause catastrophic failure. (See 5.2.)

4.2 Cooling equipment operation

When performing tests to verify ONAN thermal characteristics, all forced air cooling equipment should be off for all three tests. When performing tests to verify thermal characteristics of forced cooled ratings, all three tests should be performed with cooling equipment, pumps and fans, appropriate for the forced cooled rating, in operation when applying load. Pumps used with the cooling equipment should remain in operation during resistance measurements. Fans may be turned off or left on during resistance measurements, as agreed upon by the manufacturer and the user.

5. Precautions

Risks are associated with performing temperature rise tests at loads beyond nameplate rating, similar to the risks associated with operating a transformer beyond its nameplate rating. Risks associated with operating transformers beyond nameplate rating are discussed in detail in IEEE Std C57.91-1995™. Before these temperature rise tests are performed, the transformer design should be reviewed by the manufacturer to determine if there are limitations other than winding hottest spot, and the resulting insulation aging, which would limit loading of the transformer or cause failure. Risks associated with these tests are discussed in the following subclauses.

5.1 Thermal degradation

Accelerated thermal degradation will occur if the winding hottest spot temperature obtained during this test exceeds the maximum temperature rating of the insulation system. This thermal degradation may cause a small change in transformer fluid characteristics, such as increased gases dissolved in oil, increased power factor, or reductions in interfacial tension. If these changes are to be used to evaluate test results, the user and manufacturer should recognize that, presently, there are no approved standard limits on these changes, and they should agree, prior to performing these tests, what changes are permissible.

5.2 Other factors limiting loading

The following factors that may limit loading should be evaluated:

a) Hottest spot temperatures of leads, and other components other than the winding
b) Oil expansion space
c) Stray flux heating of components
d) Bushing loading capability
e) Lead and cable temperatures
f) Current-carrying capability of tap changers for energized and deenergized operation
g) Load-tap-changer interrupting capability
h) Current transformer ratings
i) Evolution of gas bubbles from insulation
j) Thermal capability of other associated equipment

5.3 Monitoring of test results

Data taken as the test series progresses should be monitored and analyzed to reduce the risk of damage. Data recorded during tests per 9.5 and 9.6 should be evaluated to determine if excessive hottest spot temperatures, top oil temperatures, or oil levels may occur during tests per 9.7 or Clause 10. A preliminary oil exponent n, top oil temperature, and hottest spot temperature may be determined from test data obtained in 9.5 and 9.6 and used to estimate the maximum temperatures during tests per 9.7 or Clause 10.

To minimize the risk of damage to the transformer, the thermal characteristics determined from 9.8, in conjunction with the equations from the loading guides,[6] should be used to calculate the maximum temperature rises expected prior to performing the load cycle test per Clause 10. If thermal characteristics have not been verified by tests in accordance with Clause 9, the expected temperature rises should be calculated using design data prior to performing the test procedures in Clause 10.

Oil expansion and pressure limitations should be evaluated using the measured data recorded in tests per Clause 9, if performed. In the absence of test data, calculated values of oil expansion and pressure, based on design data, should be used for evaluation.

[6]See Clause 2 for list of loading guide standards or Annex A for equations.

5.4 Maximum temperatures

It is suggested the hottest spot be limited to 140 ˚C, and the top oil be limited to 110 ˚C, unless other values are agreed upon by the manufacturer and user. If it becomes apparent that excessive values may be obtained, the load specified in 9.7 should be reduced from the 125% value such that the top oil temperature, hottest spot temperatures, and oil levels are limited to acceptable values.

6. Monitored data

Data specified in 6.1 through 6.4 should be recorded for all tests. Unless otherwise specified, it should be recorded at intervals of 15 min, or less, until the top oil temperature change is less than 5 ˚C per hour, and at intervals of 30 min or less thereafter.

Test system accuracy for each quantity measured should fall within the limits specified in IEEE Std C57.12.00-2000™, Table 21.

6.1 Ambient air temperature

Ambient air temperature should be measured in accordance with IEEE Std C57.12.90-1999™.

6.2 Oil temperatures

The top oil temperature should be measured using one or more thermocouples or suitable thermometers immersed approximately 50 mm below the top oil surface.

Oil temperatures at the top and bottom of at least one radiator or heat exchanger should be measured using a thermocouple or a suitable measuring device in a suitable location to measure the average temperature of inlet and outlet oil. The radiator(s) or heat exchanger(s) selected should be those whose inlet and outlet oil temperatures are representative of the average temperatures of all radiators or coolers.

6.3 Other temperatures

Temperatures measured by fiber optic temperature sensors should be recorded on transformers equipped with these devices.

6.4 Currents

Input currents should be measured with an accuracy of ±0.5% and held constant within ±1.0%.

7. Recorded data

The data listed in 7.1 through 7.3 should be recorded at the conclusion of each test.

7.1 Losses

Input losses (W) should be recorded at stability and after the cutback to rated current.

7.2 Temperature indicator readings

The following additional temperature measurements should be recorded if the transformer is equipped with the appropriate device.

a) Top oil temperature, as indicated by the transformer liquid temperature indicator
b) Winding temperature readings from properly calibrated, simulated, or direct reading winding temperature indicators

7.3 Tank surface and other temperatures

Tank surface temperatures should be measured by infrared scanning or other suitable external temperature monitoring methods when specified. Surfaces with temperatures exceeding the top oil temperature by more than 20 °C should be monitored and recorded.

7.4 Oil levels

For all transformers, except those with conservator-type oil preservation systems, the change in oil level due to temperature change should be determined from measurement of distance between the top oil level and the top of the manhole flange.

8. Oil samples

Oil samples should be taken immediately before and after each temperature rise test per 9.5, and immediately after each temperature rise test per 9.6 and 9.7. One sample should be taken within one hour of the completion of the temperature rise tests, and an additional four consecutive samples should be taken at approximately two-hour intervals thereafter. When prior experience indicates that more or fewer samples are required, the number of samples may be changed by agreement with the manufacturer and user. Sampling procedures should be in accordance with IEEE Std C57.104-1991™.

NOTE—At the time this guide was approved, IEEE PC57.130™ was being developed for sampling and analysis of oil during factory tests. When issued, sampling instructions per IEEE PC57.130™ should supersede these recommendations.

Oil samples should be taken immediately before and immediately after the load cycle temperature rise test performed per Clause 10.

Oil samples should be representative of the bulk of the oil in the transformer and taken at locations where the oil circulates freely and is well mixed. In some cases, particularly for transformers without forced (directed) oil flow, where oil may flow more slowly through the windings, it may be necessary to continue sampling after the end of the test to obtain reasonably uniform distribution of any generated fault gases into the total oil volume.

9. Test procedure for determining the thermal characteristics of oil-immersed power transformers

This clause prescribes a test procedure for performing a series of temperature rise tests on a transformer for the purpose of determining those thermal characteristics required to calculate the thermal performance of the transformer using the equations in the loading guides. These thermal characteristics and equations may be used to predict the transformer's performance during loading conditions other than at rated conditions.

Tests should be performed using the procedures specified for the short-circuit method of simulating load per IEEE Std C57.12.90-1999™, except when otherwise specified in this recommended practice. Where procedures described in this document and IEEE Std C57.12.90-1999™ differ, the procedures recommended in this document are preferred. The cooling curve method shall be used to determine average winding temperature rises.

9.1 Tap position and connection

The transformer should be tested in the combination of connections and taps specified in IEEE Std C57.12.90-1999™.

9.2 Number of tests

Temperature rise tests at three different load levels should be performed with the same cooling equipment in operation to provide data to verify the following thermal characteristics of the transformer:

a) Top oil temperature rise $\Delta\Theta_o$

b) Average winding temperature rise $\Delta\Theta_w$

c) Winding hottest spot temperature rise $\Delta\Theta_H$

d) Oil exponent n

e) Winding exponent m

f) Thermal time constant of the transformer top-oil temperature rise τ_{TO}

g) Thermal time constant of the winding temperature rise τ_W

h) Oil level change with respect to top oil temperature change

9.3 Applied test currents

The three different applied currents should be selected to produce the total losses anticipated at loads of approximately 70%, 100%, and 125% of maximum nameplate rating. These loads were arbitrarily chosen to provide test losses approximately equal to total losses of 50%, 100%, and 150% of those at rated load. Other values may be chosen, provided that the differences among losses is sufficient to determine the exponents n and m (see Clause 11).

9.4 Discontinued tests

If a test is shutdown or data are not recorded prior to reaching 80% of the change between initial and final top oil temperature rise over ambient, the test should be stopped, the oil temperatures allowed to cool down to within 5 ˚C of the initial values or the ambient air temperature, whichever occurs first, and the test started over.

If a test is shutdown or data are not recorded after reaching 80% of the change between initial and final top oil temperature rise over ambient, the test may be resumed and data taken until the top oil temperature rise above ambient does not vary by more than 2.5% or 1 ˚C, whichever is greater in a time period of three consecutive hours.

9.5 Temperature rise test at rated load

A temperature rise test holding a constant current to simulate the losses at rated load should be performed as follows.[7]

a) Short-circuit one or more windings and circulate a constant current I_{T2} equal to 100% of maximum rated current I_R plus an additional current to produce additional losses equal to the rated no-load loss. The current to be circulated may be determined using Equation (1). Maintain the current until the top oil temperature rise above ambient does not vary by more than 2.5% or 1 ˚C, whichever is greater in a time period of three consecutive hours:

$$I_{T2} = I_R\sqrt{\frac{P_R}{P_R - P_{NL}}} \tag{1}$$

b) Record all data listed in Clause 7 and Clause 8 after top oil temperature rise has stabilized and while I_{T2} is applied.

c) Reduce current to I_R and hold for a minimum of one hour. Calculate and record K_{L2} as measured current I_R for later use in 9.8.5.

d) Immediately before the end of the time period while I_R is being applied, record all data as specified in Clause 6 and Clause 7.

e) Remove the load current and measure a series of hot resistances of the windings at appropriate time intervals to determine the average winding temperatures rises using the cooling curve method in IEEE Std C57.12.90-1999™.

9.6 Temperature rise test at reduced load

After completion of the hot resistance readings taken per item e) of 9.5, to reduce test time, the transformer may be allowed to cool down until the top oil temperature is equal to or cooler than that calculated for a load equal to 70% of rated load. When this top oil temperature is reached, continue with a second temperature rise test at reduced load in accordance with the following:

a) Short-circuit one or more windings and circulate a constant current I_{T1} equal to 70% of rated current ($0.7 \times I_R$), plus additional current to produce losses equal to the rated no-load loss. The current to be circulated shall be determined using Equation (2). Continue with this current until the top oil temperature does not vary by more than 2.5% or 1 ˚C, whichever is greater, in a time period of three consecutive hours:

$$I_{T1} = I_{L1}\sqrt{\frac{P_{L1}}{P_{L1} - P_{NL}}} \tag{2}$$

b) Record all data listed in Clause 6 and Clause 7 after top oil temperature rise has stabilized and while I_{T1} is being applied.

c) Reduce the current to a value equal to 70% of rated current ($0.7 \times I_R$), and hold for a minimum time interval of one hour. Calculate and record K_{L2} as measured current/I_R for later use in 9.8.5.

d) At the end of the one-hour period, and while holding a current equal to 70% of rated ($0.7 \times I_R$), record all data as specified in Clause 6 and Clause 7.

[7]It is recommended that the first test be at rated load to facilitate the direct measurement of τ_o.

e) Remove the load current ($0.7 \times I_R$), and measure a series of hot resistances of the windings at appropriate time intervals to determine the average winding temperatures using the cooling curve method in IEEE Std C57.12.90-1999™. Only those windings found to be the hottest windings in data taken per item e) of 9.5 need be measured.

9.7 Temperature rise test at load beyond nameplate rating

After completing the hot resistance tests per item e) of 9.6, data recorded during tests per 9.5 and 9.6 may be evaluated to determine preliminary *n* and *m* exponents. The preliminary exponents may be used to evaluate whether an excessive top oil temperature or winding hottest spot temperature may occur during this test. It is suggested that the winding hottest spot temperature be limited to 140 °C and top oil be limited to 110 °C, unless other values are agreed upon by the manufacturer and user. The top oil temperature and the measured rate of change of the oil level with temperature may be used to evaluate whether excessive oil levels may occur during this test. If it becomes apparent that excessive values may be obtained, the load may be reduced from the 125% value, so the top oil temperature, winding hottest spot temperature, and oil level are limited to acceptable values.

After the evaluation of risk and the load beyond nameplate to be applied has been determined, proceed with the test as follows:

a) Short-circuit one or more windings, and circulate a constant current I_{T3}, at rated frequency, equal to 125% of rated current ($1.25 \times I_R$), plus additional current to produce losses equal to the rated no-load loss. The current to be circulated may be determined using Equation (3). Continue applying this current until the top oil temperature does not vary by more than 2.5% or 1 °C, whichever is greater, in a time period of three consecutive hours.

b) Record all data listed in Clause 6 and Clause 7 after the top oil temperature rise has stabilized and while I_{T3} is being applied:

$$I_{T3} = I_{L3}\sqrt{\frac{P_{L3}}{P_{L3} - P_{NL}}} \quad (3)$$

c) Reduce the current to 125% of rated current ($1.25 \times I_R$) and hold for a minimum time period of one hour. Calculate and record K_{L3} as measured current/I_R for later use in 9.8.5.

d) At the end of the one-hour period, while the current equal to 125% of rated ($1.25 \times I_R$) is being applied, record all data as specified in Clause 6 and Clause 7.

e) Remove the load current, and measure a series of hot resistances of the windings at appropriate time intervals to determine the average winding temperatures using the cooling curve method in IEEE Std C57.12.90-1999™. Only those windings found to be the hottest windings in item e) of 9.5 need be measured.

9.8 Evaluation of thermal data

The data recorded in tests per 9.5, 9.6, and 9.7 may be used to determine those thermal characteristics listed in 9.8.1 through 9.8.7, which are needed to solve the transformer loading guide equations in IEEE Std C57.91-1995™.

9.8.1 Top oil temperature rise

The ultimate top oil temperature at rated load $\Theta_{TO,R}$ and the average ambient temperature Θ_A were measured using the procedure in item b) of 9.5. The top oil temperature rise at rated load $\Delta\Theta_{TO,R}$ is the difference ($\Theta_{TO,R} - \Theta_A$).

9.8.2 Average winding temperature rise

The average winding temperature rise at each of the loads should be determined per the short-circuit method of performing temperature rise tests in IEEE Std C57.12.90-1999™.

9.8.3 Winding hottest spot temperature rise

The ultimate winding hottest spot temperature rise over top oil temperature at rated load $\Delta\Theta_{H,R}$ may be determined from the tests per 9.5 by any of the following methods, as agreed by the user and manufacturer.

9.8.3.1 Winding hottest spot temperature rise determination—method 1

The ultimate winding hottest spot temperature rise over top oil temperature may be determined from direct measurements of appropriate winding and oil temperatures using fiber optic temperature sensors, or other acceptable devices, when such devices have been installed.

9.8.3.2 Winding hottest spot temperature rise calculation—method 2

The ultimate winding hottest spot temperature rise over top oil temperature may be calculated by the manufacturer using appropriate analytical or empirical methods available as part of their design practice. The manufacturer should be able to demonstrate by design tests that the procedures used predict the ultimate winding hottest spot within an accuracy agreed upon by the manufacturer and user.

9.8.3.3 Winding hottest spot temperature rise calculation—method 3

For non-forced oil cooled transformers, the ultimate winding hottest spot temperature $\Theta_{H,R}$ may be determined using Equation (4), when agreed to by the manufacturer and user (see NOTE):

$$\Theta_{H,R} = \Theta_A + \Delta\Theta_{TO,R} + F_H \Delta\Theta_{W,R} \tag{4}$$

For forced oil cooled transformers, the ultimate winding hottest spot temperature $\Theta_{H,R}$ may be determined using Equation (5), when agreed to by the manufacturer and purchaser (see NOTE):

$$\Theta_{H,R} = \Theta_A + \Delta\Theta_{BO,R} + 2\lceil \Delta\Theta_{AO,W} - \Delta\Theta_{BO,R} \rceil + F_H \Delta\Theta_{W,R} \tag{5}$$

The ultimate winding hottest spot temperature rise over top oil temperature at rated load $\Delta\Theta_{H,R}$ is the difference between the winding hottest spot temperature at rated load $\Theta_{H,R}$ and the ultimate top oil temperature at rated load $\Theta_{TO,R}$, measured in 9.5b.

NOTE—This method has been incorporated into the IEC loading guides but has not been adopted by IEEE loading guides. Recommended values of F_H are controversial, and the manufacturer should be consulted for appropriate values. See B.3.1.3 for more information on this method and a discussion of appropriate values for F_H.

9.8.4 Top oil exponent n

Top oil temperature rises determined by tests in accordance with 9.5, 9.6, and 9.7 may be used to determine the top oil exponent n [see Annex A, Equation (A.1)]. The exponent n is the slope of the line on log-log

paper that best fits the plot of the top oil temperature rises, $\Delta\Theta_{TO,1}$, $\Delta\Theta_{TO,2}$, and $\Delta\Theta_{TO,3}$, measured in tests 9.5, 9.6, and 9.7, versus the calculated values of Equation (6) through Equation (8):

$$\left[\frac{(K_{T1})^2 R + 1}{R + 1}\right] \quad (6)$$

$$\left[\frac{(K_{T2})^2 R + 1}{R + 1}\right] \quad (7)$$

$$\left[\frac{(K_{T3})^2 R + 1}{R + 1}\right] \quad (8)$$

where K_{T1}, K_{T2}, and K_{T3} are the per unit loads simulated by the three temperature rise tests, as calculated per Equation (9) through Equation (11):

$$K_{T1} = \frac{I_{t1}}{I_R}\sqrt{\frac{P_{L1} - P_{NL}}{P_{L1}}} \quad (9)$$

$$K_{T2} = \frac{I_{t2}}{I_R}\sqrt{\frac{P_{L2} - P_{NL}}{P_{L2}}} \quad (10)$$

$$K_{T3} = \frac{I_{t3}}{I_R}\sqrt{\frac{P_{L3} - P_{NL}}{P_{L3}}} \quad (11)$$

The slope of the line may be determined by the slope of the line that best fits the data points plotted using the least-squares method.

9.8.5 Winding exponent *m*

The average winding temperature rise above average oil temperature from 9.5, 9.6, and 9.7 may be used to determine the exponent m in Equation (A.2). The exponent m may be determined by the line that best fits the data points determined from tests 9.5, 9.6, and 9.7, plotting $\Delta\Theta_{W1}$, $\Delta\Theta_{W2}$, and $\Delta\Theta_{W3}$ against K_{L1}, K_{L2}, and K_{L3}, on log-log paper. The exponent m is equal to one-half of the slope ($2 \times \mathrm{m}$) of this line. The slope of the line may be determined by the slope of the line that best fits the data points plotted using the least-squares method.

9.8.6 Oil time constant

The thermal time constant of the oil may be determined by either of two test methods given in 9.8.6.1 or 9.8.6.2. Overall, 9.8.6.1 generally produces shorter time constants than does 9.8.6.2 and is recommended as more conservative. On the other hand, 9.8.6.2 is included as a reference method when the time constant during cool down is needed.

9.8.6.1 Oil time constant during heat up

Starting with the oil at an equilibrium temperature for a first level of load (or no load), increase the load to a higher value and record the oil temperature at suitable time intervals until the ultimate temperature rise is reached. The oil time constant is equal to the time required for the oil temperature to change by 63% of the ultimate temperature change.

9.8.6.2 Oil time constant during cool-down

Starting the oil at an equilibrium temperature for a fixed level of load, totally remove the load and record the oil temperatures at suitable time intervals until the oil approaches the ambient temperature. The top oil time constant τ_{TO} is equal to the time at which $(\Delta\Theta_{TO} - \Delta\Theta_{TO,\,i})$ has decayed to 37% of its initial value $(\Delta\Theta_{TO,\,U} - \Delta\Theta_{TO,\,i})$.

9.8.7 Winding time constant

A winding time constant τ_W may be calculated from the hot winding resistance measurements taken to establish the average winding temperature rise over the average oil temperature.[8] First, the measured hot winding resistance versus time readings should be converted to average winding temperatures versus time data. Then, the average oil temperature versus time should be determined from the average of top oil and bottom oil measured temperatures at each time interval. Subtracting the average oil temperature from the average winding temperature at each time interval yields the average winding temperature rise over average oil temperature data needed to determine the time constant τ_W. The winding time constant can be determined from the data by plotting the average winding temperature rise over average oil temperature versus time on semi-log graph paper, using the *least-squares* method to obtain the best-fitting straight line. The winding time constant τ_W is equal to the time required for the average winding temperature rise over average oil temperature to decay to 37% of its initial value.

9.9 Evaluation of other data

Because of the short duration (hours) of the temperature rise tests, evaluation by dissolved gas analysis procedures in IEEE Std C57.104-1991™ may not be applicable to gases collected before and after a temperature rise test. IEEE PC57.130™ currently under development will provide guidance for evaluating by dissolved gases. Until IEEE PC57.130™ is issued, pass-fail criteria based on dissolved gases may be established by mutual agreement of user and manufacturer prior to the test.

10. Test procedure for performing load cycle temperature rise tests

This clause covers a recommended procedure for performing a temperature rise test to demonstrate a transformer's capability to be loaded with a specific sequence of loads, including loads beyond nameplate rating for specific time intervals.

10.1 Recommended prior tests

It is recommended that the thermal characteristics of the transformer be determined in accordance with Clause 9 prior to performing this load cycle test.

10.2 Information specified by user

The user needs to supply the following information prior to starting this test:

a) Load cycle

b) Maximum permissible winding hottest spot temperature rise over ambient air temperature

c) Maximum permissible top oil temperature rise over ambient air temperature

[8]This method may not be applicable or reliable for transformers with nondirected flow, forced oil cooling.

d) Maximum permissible level of combustible gases dissolved in the oil, when dissolved gases are to be used for evaluation of satisfactory performance

e) Maximum acceptable loss of life

10.3 Determination of load cycle

The sequence of test loads and the time duration should be representative of the user's anticipated operating conditions (daily load cycle), and it should be specified by the user. The representative test load cycle (L_c through L_j) should be selected in steps of loads (L_1, L_2, L_3,...L_j), each remaining constant over its time interval ($t_1 - t_0$), ($t_2 - t_1$), ($t_3 - t_2$),...($t_j - t_{j-1}$) (see Figure 1). Preferably, the minimum time interval should be one hour, except for the maximum load duration, which may have a shorter time interval than one hour. The loads selected may be the arithmetic average of the loads over time intervals of one hour or less. For time intervals longer than one hour, the RMS load for the period should be used.

The loads to be applied should be sequenced such that the load for the final interval (L_j) is that load calculated to produce the maximum hottest spot temperature. The initial load (L_1) should be the load during an interval of the load cycle that occurs at least 12 hours prior to the interval of the final load.

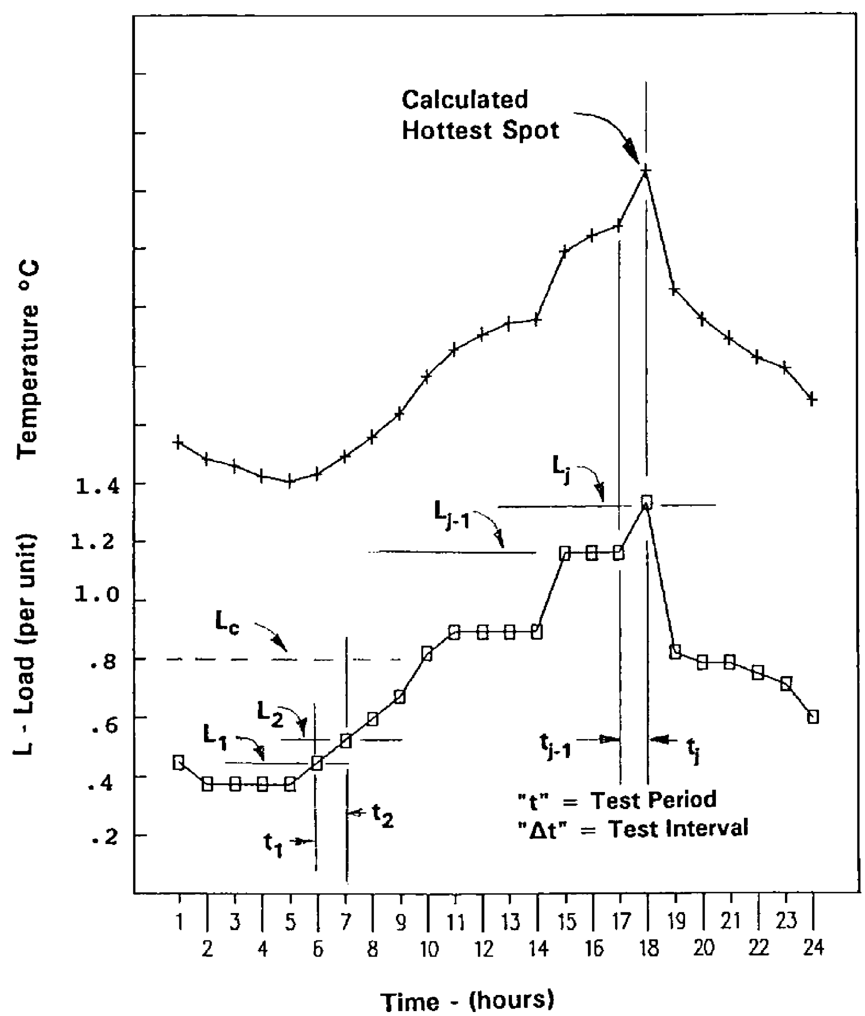

Figure 1—Determination of test load cycle from daily load cycle

10.4 Preparatory calculations

The current required for the conditioning load and the input current for each load step should be calculated prior to beginning the test.

10.4.1 Conditioning load

A conditioning load L_c should be applied prior to the initial load L_1 to bring the initial top oil temperature rise $\Delta\Theta_{TO,\,i}$ to a value representative of the top oil temperature rise, which would occur at the time t_0 in the load cycle. This initial top oil temperature rise may be calculated using Equation (12):

$$\Delta\Theta_{TO,\,i} = \Delta\Theta_{TO,\,R}\left[\frac{K_c^2 R + 1}{R + 1}\right]^n \tag{12}$$

K_c, the ratio of the conditioning to the rated load, is calculated with Equation (13):

$$K_c = \frac{L_c}{L_R} \tag{13}$$

L_c is the RMS load of a 12-hour period preceding the period in the load cycle selected for the initial load. L_c may be calculated per Equation (14):

$$L_c = \sqrt{\frac{\Sigma\,(L_J^2\ t_J)}{\Sigma t_J}} \tag{14}$$

10.4.2 Input currents to simulate loads

Calculate the increase in current required to generate equivalent total losses for each loading condition in the load cycle test. The following procedure should be used:

a) Calculate the ratio $1/R$ of no-load loss to load loss at rated load.

b) Calculate K for loading condition L_1, L_2, $L_3 \ldots L_j$.

c) From Figure 2, determine the percent increase in load current required for $(I_{nj})\Omega$ to equal the no-load loss. Calculate I_{n1}, I_{n2}, I_{n3},...I_{nj} by multiplying this percent increase times the load current/100.

The input current to be held for each interval is the sum of the load current for that interval I_{Lj} and the increase in current I_{nj}.

10.5 Data recorded

Data listed in Clause 6, subclause 7.1, and subclause 7.2 should be measured and recorded during this test at intervals of 15 min, or less, and at the end of each load interval.

10.6 Test procedure

a) Short-circuit one or more windings, and circulate conditioning load current I_c until the top oil temperature rise reaches $\Delta\Theta_{TO,\,i}$. The load cycle temperature rise test may be started after the transformer top oil temperature rise has been stabilized for two hours at a temperature rise equal to $\Delta\Theta_{TO,\,i}$ plus/minus 2.5% or 1 ˚C, whichever is greater.

b) After the conditioning temperature has stabilized, record the data listed in Clause 6 and adjust the circulated current to a value equal to $(I_{L1} + I_{n1})$ for time interval t_1.

c) At the end of time interval t_1, adjust current to $(I_{L2} + I_{n2})$ and hold for time interval t_2.

d) Repeat step c) of 10.6 for each of the time intervals from t_2 to t_j, with an appropriate adjustment of current to compensate for no-load loss at each interval.

e) At the end of time interval $t_j - 1$, adjust current to $(I_{Lj} + I_{nj})$ and hold for time interval t_j. At the end of time interval t_j, shut down and measure hot resistance to determine the average winding temperature using the cooling curve method of IEEE Std C57.12.90-1999™.

f) Correct the measured average winding temperature rise to current I_{Lj} using the method specified in the short-circuit method section of IEEE Std C57.12.90-1999™.

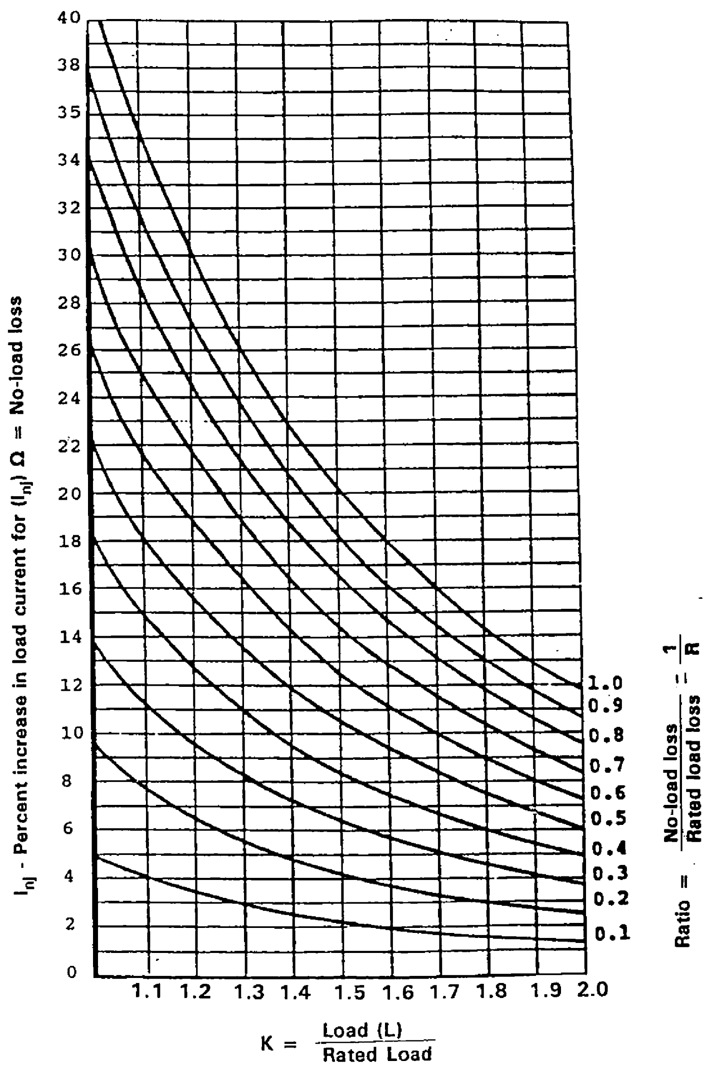

Figure 2—Curve to determine I_{nj}, the incremental curve to be added to the load current so that test losses equal total losses

10.7 Interrupted test

If the test is shutdown, or data are not recorded during the load cycle test because of equipment malfunction or other reasons, the test should be started over with the top oil temperature stabilized at $\Delta\Theta_{TO,i}$. This is

necessary because any interruption in the required load cycle would be a nonconformance to the load cycle being certified. Fans and pumps may be run during the cooling period to obtain the required initial temperature rises.

10.8 Assessment of transformer performance

The load cycle temperature rise test will demonstrate a transformer's specified performance when loaded in accordance with the specified loading sequence, if the following conditions are met:

a) Winding hottest-spot temperature rise over ambient air temperature does not exceed that specified by the user for the specified load cycle.
b) Top oil temperature rise over ambient air temperature does not exceed that specified by the user for the conditions tested.
c) Tank surface temperature does not exceed the maximum allowable temperature for other metallic hot-spot temperatures (in contact and not in contact with insulation) given in the loading guides for the appropriate transformer rating and type of loading.
d) Transformer tank oil does not spill.
e) Bushings do not leak.
f) The quantity and composition of the gases in the oil before and after the test are within acceptable limits established prior to the test. (See 9.9.)

If either the top oil temperature rise or the average winding temperature rise obtained from the load cycle temperature rise test does not confirm the values predicted by calculation, then the exponents and time constants used in the loading guide equations may be modified accordingly when used to determine temperature rises for this particular transformer.

11. Integrated test procedure for determining thermal characteristics and for performing load cycle temperature rise tests

This clause describes a recommended procedure for a combined temperature rise test that can be used in place of tests described in Clause 9 and Clause 10 whenever the load profile may be represented by three discrete loads, with the maximum load not exceeding a value, agreed upon by the manufacturer and user, which may be applied for time duration required for the top oil temperature to stabilize.

11.1 Load cycle simulation

A key requirement for the use of this integrated test procedure is to have a load test profile, which includes short-time or long-time loads in excess of nameplate rating, and which may be simulated by a thermally equivalent continuous load of a value acceptable to the manufacturer and user. This equivalent maximum load along with loads at 100% and at 70% of nameplate rating can provide the thermal data required to both simulate the maximum temperatures that may occur during the load cycle and provide data necessary to determine the thermal characteristics of the transformer.

11.2 Preliminary evaluation

The expected top oil and winding hottest spot temperature rises for those selected test loads beyond nameplate rating may be calculated using design data and formulae in IEEE Std C57.91-1995™, prior to performing the test. The transformer design may be checked to determine if there are limitations other than insulation aging, which would limit the loading of the transformer or cause catastrophic failure (see 5.2).

These limitations may be reviewed with respect to the temperatures anticipated to occur during this load cycle temperature rise test.

11.3 Test procedure

The basic combined test procedure consists of the following steps:

a) Perform a temperature rise test at 100% of maximum nameplate rating in accordance with 9.5.
b) Perform a temperature rise test similar to 9.7, while applying a load calculated to have the same temperature rises as the load cycle profile that is being simulated.
c) Perform a test at approximately 70% of maximum nameplate rating per 9.6.
d) Record all data specified in Clause 6 through Clause 8 for each of these tests.

11.4 Initial test

Testing should begin with a temperature rise test at rated load, as described in 9.5. Sequential shutdowns are made to determine the average winding temperature of each winding at equilibrium by measuring winding resistance. Hot resistance readings on subsequent shutdowns shall be taken on the winding with the highest average winding temperature.

Winding time constants may also be determined from the winding resistance cool-down readings, taken as described in 9.8.7.

11.5 Conditioning load

The initial or conditioning load established just prior to beginning the beyond maximum nameplate load profile test should be determined per 10.4.1. If the top oil temperature remaining after completion of the initial test (see 11.4) is higher than the required initial top oil temperature, the load cycle test may be started when the top oil temperature has cooled to the required initial temperature.

11.6 Beyond maximum nameplate test

A beyond maximum nameplate load that produces a steady state hottest spot temperature equal to the maximum hottest spot calculated for the specified load cycle should be determined as described in 10.3. During this beyond nameplate loading, test data should be collected as indicated in Clause 6 and Clause 7.

During the beyond nameplate load profile test, all of the necessary data should be recorded for assessment of the transformer's performance as described in 9.8.

11.7 Final test

Immediately after the beyond maximum nameplate load profile test is complete, the load should be reduced to 70% of maximum nameplate rating while full cooling is maintained. During cool down to the 70% load, hot resistance measurements may be recorded to determine the oil time constant during cool down, as described in 9.8.6.2.

Annex A

(normative)

Loading guide equations

A.1 Explanation of equations

The present loading guide IEEE Std C57.91-1995™ and previous loading guides IEEE Std C57.92-1981™ and IEEE Std C57.115-1991™ used equations to determine the top oil temperature rises and winding hottest spot temperature rises of transformers at loads other than nameplate rating. The symbols used in the equations of these documents were not used consistently. To avoid confusion, these equations have been rewritten in this annex using the new symbols adopted in 1988, to be consistent with the symbols used throughout this document.

A.2 Ultimate top oil rise for load L

ANSI C57.92-1981, Equation (6), and IEEE Std C57.115-1990™, Equation (3), are rewritten as Equation (A.1):

$$\Delta\Theta_{TO,\,U} = \Delta\Theta_{TO,\,R}\left[\frac{K^2R+1}{R+1}\right]^n \tag{A.1}$$

A.3 Ultimate winding hottest spot temperature rise over top oil for load L

IEEE Std C57.92-1981™, Equation (7), and IEEE Std C57.115-1991™, Equation (4), are rewritten as Equation (A.2):

$$\Delta\Theta_{H,\,u} = \Delta\Theta_{H,\,R}\,K^{2m} \tag{A.2}$$

A.4 Transient heating equation for top oil rise over ambient temperature

IEEE Std C57.92-1981™, Equation (5), and IEEE Std C57.115-1991™, Equation (2), are rewritten as Equation (A.3):

$$\Delta\Theta_{TO} = (\Delta\Theta_{TO,\,U} - \Delta\Theta_{TO,\,i})\left(l - e^{\frac{-t}{\tau_{TO}}}\right) + \Delta\Theta_{TO,\,i} \tag{A.3}$$

A.5 Hottest spot temperature

IEEE Std C57.92-1981™, Equation (4), and IEEE Std C57.115-1991™, Equation (1), are rewritten as Equation (A.4):

$$\Theta_H = \Theta_A + \Delta\Theta_{TO} + \Delta\Theta_{H,\,U} \tag{A.4}$$

A.6 Thermal capacity

A.6.1 Nondirected flow transformers

C is the 0.1323 (weight of core and coil assembly in kilograms) + 0.08818 (weight of tank and fittings in kilograms) + 0.3513 (liters of oil)

A.6.2 Directed flow transformers

C is the 0.1323 (weight of core and coil assembly in kilograms) + 0.1323 (weight of tank and fittings in kilograms) + 0.5099 (liters of oil)

A.7 Time constants

The top oil time constant at rated kilovoltamperes from the present loading guide IEEE Std C57.91-1995™, Equation (7.10), and former loading guides IEEE Std C57.92-1981™, Equation (9), and IEEE Std C57.115-1991™, Equation (6), is rewritten as Equation (A.5):

$$\tau_{TO,R} = \frac{C\Delta\Theta_{TO,R}}{P_{T,R}} \tag{A.5}$$

The top oil time constant at any starting temperature and for any load is given by IEEE Std C57.91.1995™, Equation (7.11), IEEE Std C57.92-1981™, Equation (10), and IEEE Std C57.115-1991™, Equation (7). These equations are rewritten as Equation (A.6):

$$\tau_{TO} = \tau_{TO,R}\frac{\left(\frac{\Delta\Theta_{TO,U}}{\Delta\Theta_{TO,R}}\right) - \left(\frac{\Delta\Theta_{TO,i}}{\Delta\Theta_{TO,R}}\right)}{\left(\frac{\Delta\Theta_{TO,U}}{\Delta\Theta_{TO,R}}\right)^{1/n} - \left(\frac{\Delta\Theta_{TO,i}}{\Delta\Theta_{TO,R}}\right)^{1/n}} \tag{A.6}$$

Annex B

(informative)

Tutorial

B.1 Transformer temperature considerations

Because the general relationship between insulation aging rate and operating temperatures is well known, transformer operating temperatures under the many various environmental conditions and transient loading conditions are a primary concern of the transformer user. It is generally understood by most transformer users that the kilovoltampere rating of a transformer is a benchmark rating representing the maximum continuous load current that a transformer can carry within the prescribed standard temperature rise limitations. Further, it is recognized that the actual conditions experienced by a transformer in service do not generally correspond to the steady, standard conditions on which standard ratings are based. For example, heat generated by losses in the transformer is proportional to the square of the applied loads, which are not steady, but changing throughout the day, as well as with the seasons. Also, the heat dissipation from the transformer is affected by external conditions such as ambient air temperature, prevailing wind velocity and direction, and solar heating, which are continuously changing. Therefore, the maximum peak load that a transformer can carry will depend on the service conditions at the time the load is applied and the maximum operating temperatures allowed by the user.

Various guidelines have been used to predict the maximum load that a transformer should carry under various operating conditions and environments. The operating practices of many users, factory test data, and service data have provided input into the development and refinement of recommended loading practices. These operating practices have been incorporated by the IEEE Transformers Committee into Transformer Loading Guides,[9] which provide recommendations for determining the permissible loading of a transformer under a variety of service conditions and allowable maximum temperatures. These guides, which are based on theory combined with empirical data accumulated during years of transformer testing and operation by the various manufacturers and users, are considered to be conservative operating practices. Prior to the work on this recommended practice, little testing had been performed to determine the operating temperatures under actual operating load conditions, because of the technical difficulties and expense of performing such tests.

B.2 History

In the mid-1970s, one utility performed measurements of transformer temperature rises on a number of transformers at loads beyond nameplate rating to verify the ability of the transformers to withstand possible overload contingencies. It was observed that the temperatures measured on transformers under various loads did not correlate well with the temperatures predicted by the equations and charts in loading guide ANSI C57.92-1981. This observation was reported to the Thermal Test Working Group of the IEEE Transformers Committee with a request that the accuracy of the equations used in the Loading Guides be reviewed.[10]

The Working Group reviewed the equations in the Loading Guides and concluded that the equations represented state-of-the-art knowledge of a transformer's thermal response to nonstandard loading conditions, provided that the correct values of exponents and time constants were used. Discrepancies

[9]See Clause 2.

[10]Letter from Paul Q. Nelson, Southern California Edison Co., to R. Veitch, Chairman, Working Group on Thermal Test, IEEE/PES Transformers Committee, 22 March 1976.

between calculated temperatures and temperatures measured during operation were, most likely, due to use of assumed *typical* values of exponents and time constants in the equations used to predict the transformer temperatures during operating conditions. A task force was assigned to draft a test procedure that could be used to determine the exponents and time constants for transformers in a consistent manner. It was anticipated that an accumulation of this data in conjunction with actual measurements of transformers in service would provide the data necessary to determine if the equations in the loading guides could be improved.

During the early balloting of the procedure to determine the exponents and time constants of a transformer, a number of negative ballots indicated dissatisfaction with the original scope of the procedure. A number of working group members were in need of a test procedure that could be specified to verify that a transformer could be loaded with a specified load cycle. Negative ballots were cast because the proposed test procedure being balloted did not meet this need. In order to resolve the negative ballots, it was decided to expand the scope to include test procedures for both purposes. The draft would be modified to add an additional test procedure to demonstrate that a transformer could be loaded with a specified load cycle without exceeding specified temperature rises.

Subsequently, during the final balloting process of the expanded document, a negative ballot was filed, petitioning for a combined test procedure to reduce the test time and costs. The combined procedure would be an adaptation of the procedure to determine time constants and exponents, modified to replace the recommended 70%, 100%, and 125% loads with three loads, which would simulate a user's specific load cycle. One of the three loads would simulate the maximum load conditions in the specified load cycle producing the winding hottest spot temperature. The scope of the document was again extended to include this combined procedure as a third alternative test procedure.

As work progressed on the draft of this test procedure, two EPRI projects on Transformer Life Characteristics were completed. Project RP-1289-1 [B6] and RP-1289-2 [B7] included overload testing of full-size transformers to study the parameters affecting transformer loss of life during overloads. Knowledge gained from these two projects was incorporated into these test procedures.

B.3 Problems determining thermal characteristics

The first problem facing the working group was to develop a test procedure to determine the exponents and time constants for a specific transformer. During a standard transformer thermal test, oil temperature rises are measured and winding temperature rises are determined from winding resistance data taken only after thermal stability has been reached at maximum load. This provides only one data point for the determination of a load versus temperature rise relationship. Additional data points are required to empirically determine the exponents of load versus temperature rise used in the equations of the loading guides. The opinion of the working group developing this procedure was that two tests were not accurate enough and that three tests would be an acceptable compromise between economic considerations and statistical accuracy. The increments of load (70%, 100%, and 125%) to be used for the three tests were arbitrarily selected to provide a reasonably accurate spread between data points.

During the development of this test procedure, many technical issues were addressed concerning conflicts in assumptions made to develop the loading guides equations and the standard thermal test procedures in IEEE Std C57.12.90-1999™. The more important issues were

a) Winding hottest spot determination

b) Temperature rise testing at constant losses or constant current

c) Ohmic resistance and oil viscosity changes with temperature

d) Losses and load current relationships

B.3.1 Winding hottest spot temperature determination

IEEE Std C57.12.00-2000™ specifies that the winding hottest spot temperature rise over ambient shall not exceed 80 ˚C for a 65 ˚C rated transformer. At the time this document was written, the test codes did not contain a standard test method for verifying that the hottest spot temperature of a transformer met this requirement. Although the loading guides use the winding hottest spot temperature to limit loading, there is no standard test procedure for measuring the winding hottest spot temperature, nor is there a standard calculation procedure for estimating it.

Negative ballots were received on later drafts of this recommended practice objecting to the lack of a standard method of determining the hottest spot temperature rise. Because no standard procedure existed, and it was anticipated that efforts to establish one would create additional delays for this document, these negatives were resolved by adding known methods of determining the hottest spot temperature and requiring the user and manufacturer to agree on the method prior to performing the test. The following methods are known to have been used over the years and were originally considered for inclusion in this document. It was the consensus of the voting members that method a) be deleted:

a) Standard winding hottest spot temperature rise allowances suggested by the loading guides
b) Manufacturer's proprietary, empirical thermal calculations
c) IEC Loading Guide equations [B9] using winding temperature and oil temperature data obtained during standard temperature rise tests
d) Measurements of the winding temperatures using fiber optic temperature sensors on transformers specially equipped with such devices.

Each method has advantages and disadvantages, and a lack of agreement has been partially responsible for a method not being written into the standards. Upon recommendation of the working group, the IEEE Transformers Committee established a task force to study and resolve this important omission in the present standards.

B.3.1.1 Standard winding hottest spot temperature rise allowances

ANSI/IEEE loading guides recommend that the winding hottest spot temperature at rated load be determined by adding 15 ˚C for 65 ˚C (10 ˚C for 55 ˚C) rise transformers to the average winding temperature.[11] Apparently, these were derived from the difference between the guaranteed hottest spot rise of 80 ˚C (65 ˚C) and the guaranteed average winding rise of 65 ˚C (55 ˚C). Although generally assumed to be a conservative number, recent publications [B13] indicate this may not always be true. Transformers could be designed, in accordance with the IEEE standard requirements of IEEE Std C57.12.00-2000™, to meet the 80 ˚C (65 ˚C) hottest spot temperature rise guarantee with an average winding temperature rise less than 65 ˚C (55 ˚C), therefore, having a hottest spot allowance greater than 15 ˚C (10 ˚C). Because of the possibility of this occurrence, the standard allowance is considered to be the least reliable method of evaluating the winding hottest spot conductor temperature. The task force on Hottest Spot Temperature Rise Determination recommended this method be dropped from draft 13 of this recommended practice, and this was approved at the Thermal Test working group meeting in March 1995.

B.3.1.2 Manufacturers calculated winding hottest spot allowances

When requested, manufacturers may provide calculated values for a specific transformer. The calculated values are generally based on analytic methods that consider eddy current losses in the winding, insulation on conductors, ducting arrangements, and other proprietary design information. When these algorithms have

[11]IEEE Std C57.91-1995™, subclause 8.1.2, and previous standards IEEE Std C57.92-1981™, Equation (8), IEEE Std C57.115-1991™, Equation (5).

been verified by tests on models and prototypes, hottest spot temperatures calculated by these methods are preferred over the standard hottest spot allowances.

B.3.1.3 IEC calculations using data from standard temperature rise tests

For transformers without forced oil cooling, the IEC Loading Guide [B9] recommends that Equation (B.1) be used to calculate the winding hottest spot temperature at any load K times rated load:

$$\ni_{H,\,U} = \Theta_A + \Delta\Theta_{TO,\,R}\left[\frac{1 + R\ K^2}{1 + R}\right]^n + F_H\ \Delta\Theta_W\ K^{2m} \tag{B.1}$$

For transformers with forced oil cooling, studies indicated that the transformer top oil temperature, as used in Equation (B.1), was not a good reference to determine the winding hottest spot temperature. Equation (B.2) using the bottom oil temperature and the average oil temperature in the winding ducts was recommended to calculate the winding hottest spot temperature at any load K times the rated kilovoltampere:

$$\ni_{H,\,U} = \Theta_A + \Delta\Theta_{BO}\left[\frac{1 + R\ K^2}{1 + R}\right]^n + 2[\Delta\Theta_{AO,\,W} - \Delta\Theta_{BO}]K^m + F_H\Delta\Theta_W\ K^{2m} \tag{B.2}$$

At rated load, $K = 1$, Equation (B.1) and Equation (B.2) reduce to Equation (B.3) and Equation (B.4), respectively, which are in a form suitable to be used to evaluate the hottest spot allowance from data obtained from a standard temperature rise test:

$$\Theta_{H,\,U} = \Theta_A + \Delta\Theta_{TO,\,U} + F_H\Delta\Theta_{W,\,U} \tag{B.3}$$

$$\Theta_{H,\,U} = \Theta_A + \Delta\Theta_{BO} + 2[\Delta\Theta_{AO,\,W} - \Delta\Theta_{BO}] + F_H\Delta\Theta_W \tag{B.4}$$

These equations are derived using a simplified thermal diagram, such as Figure B.1, to represent the more complex transformer temperature distribution. To simplify the analysis, the following assumptions were made when constructing this diagram:

a) Both the winding temperature rises and the oil temperature rises between the bottom and top of the coils are linear.

b) The temperature difference between the oil in the duct and the winding conductor interface is a constant throughout the coil.

c) The difference between the mean temperature of the conductor at the top of the winding and the mean temperature of the oil in the top of the duct is equal to the difference between the average temperature of the winding and the average duct oil temperature.

Based on these assumptions, and assuming $F_H = 1$, the ultimate winding hottest spot temperature $\Theta_{H,\,U}$ may be calculated from Equation (B.3) or Equation (B.4) using oil temperature and winding temperature data measured during a temperature rise test.

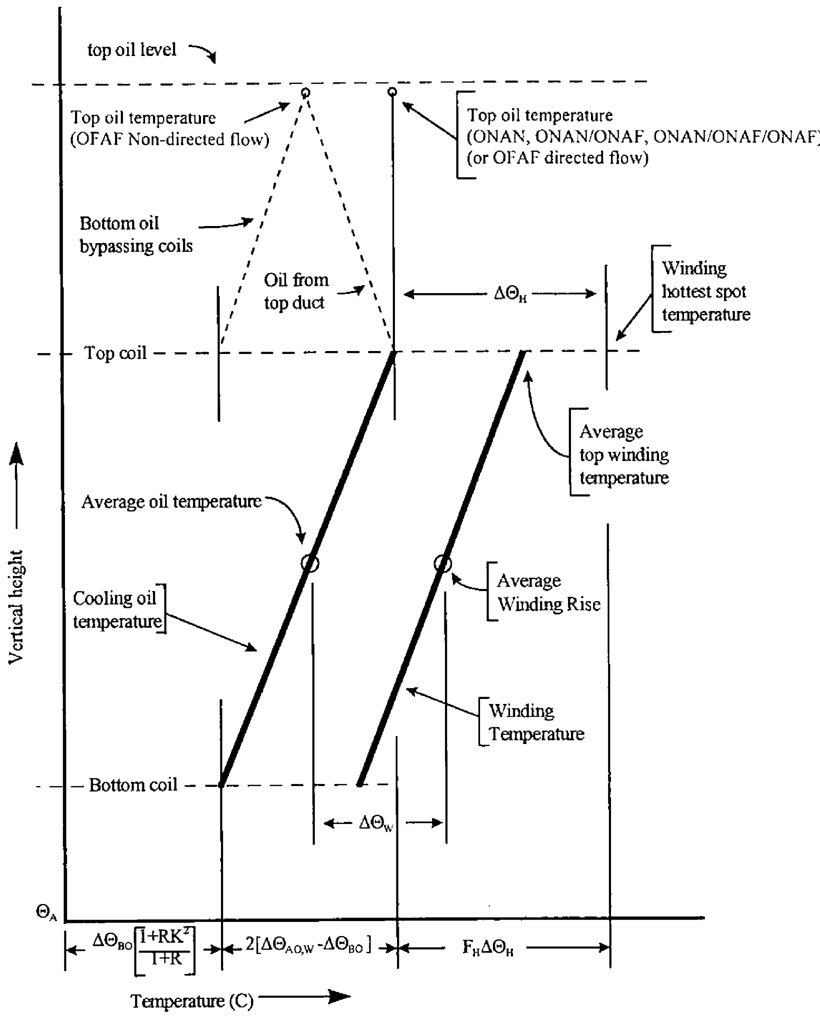

Figure B.1—Simplified diagram of transformer thermal circuit

It is recognized that the ultimate hottest spot temperature calculated using a value of $F_H = 1$ in Equation (B.3) and Equation (B.4) understates the ultimate winding hottest spot temperature and would represent the lowest limit of the winding hottest spot temperature. Increased eddy current losses at the ends of the windings, differences in duct thickness, and variations in insulation thickness and coil support structures will cause the winding temperature distribution to be nonlinear. Therefore, the winding hottest spot temperature $\Theta_{H,\,U}$ should be calculated with a hottest-spot factor F_H greater than 1 to account for the nonlinearity of the temperature distribution. IEC 60076-2 [B8] states, "This factor is assumed to be from 1.1 in distribution transformers, to 1.3 in medium power transformers. In large power transformers there is considerable variation depending on design, and the manufacture should be consulted for information, unless actual measurements are carried out." Loading Guide IEC 354 [B9] states that F_H "may vary from 1.1 to 1.5 depending upon transformer size, short circuit impedance and winding design. For the production of tables and figures in section 3 (of IEC 354), a value of 1.1 has been used for distribution transformer and 1.3 for medium, large power transformers." A report [B12], summarizing CIGRE Working Group 12-09 findings of F_H values ranging between 1.1 and 2.2, suggests 1.3 be used for power transformers under 100 MVA and 1.5 for higher ratings. Methods [B13] to determine F_H as a function of coil geometry and types of internal heat transfer have been proposed, but no standard method has been adopted.

It is important to note that the average oil temperature used in Equation (B.2) and Equation (B.4) should be the average temperature of the oil in the coil ducts, which may be different than the mean oil temperature calculated from top and bottom oil temperature measurements. The measured top oil temperature is the temperature of mixed oil from all heat sources in the transformer and may be significantly different from the temperature of the oil exiting the top of the winding containing the hottest spot. This is particularly true when forced oil cooling equipment is used. Presently, there is no standard method of determining the average temperature of the oil in the winding, and a method found to be reliable should be used. For transformers without forced oil cooling, the average of the top and bottom oil temperature measurements is frequently used, recognizing that this is a potential source of error.

B.3.1.4 Direct measurements of winding hottest spot temperatures

Direct reading temperature measurement devices, using fiber optic sensors and computerized data analysis, or similar technology, are currently available and in use in some larger power transformers to measure temperatures of the winding and the oil within the winding. Justification of the added costs has limited the usage of these devices to experimental applications or transformers with special loads. These devices provide the capability to directly measure the winding hottest spot temperature when the fiber optic sensors are located correctly in the transformer winding. A weakness of these devices is that they are capable of indicating the temperature only at the spots where the sensors are located. Therefore, their accuracy in measuring the winding hottest spot temperature is dependent on the ability to predict the location of the hottest spot prior to placement of the sensors. High temperatures in unexpected locations may not be detected and measured. However, even with these disadvantages, many consider fiber optic sensors the best tool available for measuring winding hottest spot temperatures, and their usage is increasing. It is recommended that fiber optic sensors be used for direct measurement of winding hottest spot temperatures where the additional cost can be justified. See Annex C for a discussion on the application of fiber optic sensors in transformer windings.

B.3.1.5 Evaluation of dissolved gases after temperature rise tests

Although dissolved gas analysis (DGA) technology has been used as a noninvasive method of determining that temperatures in a transformer have reached levels of concern, it is unlikely the technique will provide a means of determining the magnitude of the winding hottest spot temperature. The quantities of gases produced during the short time durations of temperature rise tests may be too small to measure significant gases accurately and repeatedly. A guide, IEEE PC57.130™, is currently being developed to provide recommendations for the sampling and interpretation of gases generated during factory tests. It may provide guidance as to whether excessive temperatures were reached, as suggested by one author [B15].

B.3.2 Constant load versus constant losses

Test Code IEEE Std C57.12.90-1999™ does not specify whether a standard temperature rise test must be performed holding constant losses or constant load current. Temperature rise tests employing the short-circuit method have been performed using either of the following methods:

a) Constant losses, equivalent to the maximum rated total losses of the transformer are held throughout the test. Applied currents are adjusted throughout the temperature rise test to compensate for ohmic resistance changes with temperature and to maintain the total losses necessary to obtain the correct top oil temperature rise.

b) A constant current, calculated to produce the rated total losses when the winding temperatures stabilize near the end of the test, is held throughout the test. Oil temperatures are adjusted by calculation, when necessary, to compensate for small differences between the final measured losses and the total losses.

Thermal time constants for transformer oil temperature rises will be different for the two methods. The second method is recommended in this recommended practice because time constants determined by this

method are considered to be more representative of the time constants needed to satisfy the equations of the Loading Guides.

B.3.3 Ohmic resistance and oil viscosity changes with temperature

There is concern that standard loading guide equations do not accurately compensate for the resistance change of the windings, nor for the fluid viscosity change with temperature. In the development of the equations of the loading guides, these two effects were assumed to effectively cancel each other. The degree of cancellation will affect the exponents n and m, hence the emphasis in this recommended practice for determining the correct values of the exponents for a given transformer when applying the equations of the loading guides.

B.3.3.1 Properties of oil affecting winding temperature rises

It is recognized that the thermochemical changes in fluid characteristics (viscosity, density, heat capacity, etc.) have an effect on the temperature rise of a transformer. As the temperature of the oil increases, the viscosity decreases, the density decreases, and the heat capacity decreases. These changes in fluid characteristics will cause small changes in the ability of the fluid to absorb heat, carry heat, and transfer heat to the cooling equipment.

The viscosity of the fluid is a measure of its resistance to flow. As the viscosity decreases, the resistance to flow decreases, permitting more fluid to flow through the coil ducts and cooling equipment on natural cooled transformers. On natural cooled transformers, the changes in viscosity may have a significant effect on transformer cooling rates. On forced cooled transformers with directed flow, this effect is not as pronounced at operating temperatures, because the viscosity changes do not have a significant effect on pump output and oil flow rates.

Large viscosity increases due to subzero temperatures will have a pronounced effect on both natural cooling and forced cooling of transformers. Large temperature differences between the winding temperatures and the oil temperatures have been reported [B2] on transformers tested, simulating cold start-up conditions at subzero temperatures. These large temperature differences are attributed to reduction in flow rate of the more viscous oil at subzero temperatures. The flow of oil in the coil ducts may be restricted by the more viscous oil near the tank wall and in the radiators or cooling panels. Users should use care in applying loads above nameplate rating to very cold transformers.

The difference in density of the hot oil in the coils and the cooler oil in the surrounding tank and cooling media is the driving force causing the thermo-siphon oil flow in natural cooled transformers. The magnitude of this force is relatively small compared with the pressures created by a pump in forced oil cooled transformers. Therefore, the variations in oil densities over the normal operating range of a transformer have little effect on the cooling of forced oil cooled transformers.

The heat capacity (specific heat) defines the quantity of heat carried by each unit volume of circulating oil. The heat capacity changes only slightly with the temperature rises normally experienced in transformers. Although the difference in specific heat between different fluids may affect performance, the variations in the specific heat of transformer oil over the operating temperature ranges of a transformer has an insignificant affect on thermal performance.

B.3.3.2 Combined effects

The thermal equations in the loading guides consider the effects of viscosity changes, density changes, and thermal capacity to be offsetting and negligible when compared with the other assumptions made in the development of the equations. It was assumed that any increased cooling effects due to changes in fluid characteristics would be offset by increased losses due to increased winding resistances at the increased

temperatures. In the procedures used in Clause 9 to develop the time constants and exponents, the variations in temperature rises due to changes in winding resistance and changes in fluid characteristics would be compensated for by empirically deriving the constants from test data.

B.3.4 Transformer temperature rise equation development

Fundamental heat transfer relationships have been empirically developed to relate heat flow rates (watts, BTU/hour) as a function of temperature differentials. The heat is generated in a transformer by the internal losses, which are a complex function of the applied loads. Users, evaluating transformer loading, needed simpler equations to determine the maximum loads a transformer could carry without exceeding allowable temperatures. Equations in the loading guides were developed by simplifying the fundamental heat transfer equations and combining them with simplified transformer loss calculations.

Equation (B.5) is a fundamental heat transfer equation relating temperature differentials and heat transfer rates by convection, which was developed using empirical techniques:

$$(N_{nu}) = k_e(N_{gr})(N_{pr})^{1.25} \tag{B.5}$$

where

(N_{nu}) is the Nusselt's number, derived from a dimensionless grouping of the heat transfer coefficient, height of surface, and thermal conductivity of fluid
(N_{gr}) is the Grashof's number, derived from a dimensionless grouping of fluid properties, physical dimensions, and temperature difference
(N_{pr}) is the Prandtl's number, derived from a dimensionless grouping of the specific heat, thermal conductivity, and viscosity of the fluid
k_e is an empirically derived constant

With appropriate assumptions of fluid properties and physical parameters, the dimensionless quantities can be reduced to Equation (B.6), which has been used for many years [B3], [B4] to evaluate the heat transfer rate from surfaces, cooled by the convection of fluids, both gases and liquids:

$$q_c = h'(\Delta\Theta)^{n''} \tag{B.6}$$

where

q_c is the heat transfer rate (W/unit area)
h' is the heat transfer coefficient, an empirical constant, varying with fluid properties, surface conditions, and physical parameters
$\Delta\Theta$ is the difference in temperature between the surface and the ambient fluid at a distance from the surface, ˚C
n'' is the empirical constant, normally 1.25 for vertical metal surfaces cooled by air

Equation (B.7), a general relationship between temperature rise and losses, may be developed from Equation (B.6) by inverting the equation and adjusting the empirical constants accordingly:

$$\Delta\Theta = h\,P^{n} \tag{B.7}$$

where

P are the total losses (W)

n is the empirical constant

h is the empirical constant

This equation has been accepted as a valid relationship when appropriate empirically determined values of h and n are chosen. From it, a relationship between temperature rises and loads, such as Equation (B.8), may be developed, where the top oil temperature at any load may be calculated if the top oil temperature rise at rated load and the exponent n are known. For example, knowing the losses P_R and top oil temperature rise $\Delta\Theta_{or}$ of a transformer load at its maximum nameplate ratings L_r, the top oil temperature rise $\Delta\Theta_{TO,\,U}$ of a transformer loaded at another load L may be calculated from Equation (B.8), if the losses P_L at that load are known:

$$\Delta\Theta_{TO,\,U} = \Delta\Theta_{TO,\,R}\left[\frac{P_L}{P_R}\right]^{n} \tag{B.8}$$

Equation (B.9), used in the transformer loading guides to evaluate transformer top oil temperatures under various loading conditions may be developed from Equation (B.8) by assuming that the ratio of losses (P_L/P_R) may be approximated by the relationship $[(K^2R+1)/(R+1)]$:

$$\Delta\Theta_{TO,\,U} = \Delta\Theta_{TO,\,R}\left[\frac{K^2\,R+1}{R+1}\right]^{n} \tag{B.9}$$

where -

R is the ratio of load loss to no load loss

K is the ratio of loads L/L_r

This substitution is an approximation, assuming the following:

a) Winding resistance does not change with temperature.

b) All eddy current and stray losses are assumed to increase with the square of the load.

c) No-load losses do not change with temperature.

Because resistance losses increase with temperature, and eddy current and stray losses vary inversely with temperature compared with the resistance losses, the total losses will be slightly less than those calculated by Equation (B.9). Consequently, the equations in the loading guides, which were developed from these relationships, are somewhat conservative and may predict temperatures slightly higher than measured during tests.

These assumptions create a problem when comparing the test data from test procedures to temperatures predicted by the equations of the loading guides. The test data available could be used to determine either the top oil temperature rise versus measured total losses or the top oil temperature rise versus the function of load $(K^2R + 1)/(R + 1)$, which is used in the loading guides to approximate the losses. The exponent n would

be different for the two methods because of the difference in the measured loss and the approximated loss. In Clause 9 of this test procedure, the exponent n is determined as a function of $(K^2R + 1)/(R + 1)$, to be consistent with its use in the equations of the loading guides.

Similarly, the loading guides define the exponent m as the exponential power of winding loss versus winding temperature rise, but uses the exponent as the exponential power of winding load versus winding hottest spot temperature rise.[12]

Because there are no standard methods for determining the winding hottest spot temperature from standard temperature rise test data, this recommended practice assumes the winding hottest spot rise will be proportional to the average winding temperature rise. The value of the exponent m is determined as the exponential power of load versus average winding temperature rise. Where direct reading hottest measurements have been taken, the exponent m should be determined by plotting the measured hottest spot temperatures versus the load.

B.4 Temperature rise testing to verify loading to a load cycle

B.4.1 Need for a load cycle test procedure

During balloting of the test procedure to determine the exponents, it became apparent that a substantial number of negative ballots being received were from members who were not satisfied with the original scope and wanted a different test procedure. In order to overcome these negative ballots, the scope was expanded to add a thermal test procedure to demonstrate that a transformer could be loaded with a particular specified load cycle, which included loads beyond the nameplate rating of the transformers. Typically, the load cycle to be used in the test would be representative of a worst-case, emergency loading situation. The purpose of the test would be to demonstrate that a transformer could withstand the specified loading cycle without significant damage beyond the normal accelerated aging due to operating the transformer at increased temperatures.

B.4.2 Test procedure difficulties

The development of a test procedure to determine the winding temperatures during such a transient loading condition presented some additional technical challenges to the working group. Because existing temperature rise test procedures required that the transformer be at both a stable loading and thermal condition when measurements are taken, a procedure had to be developed to determine temperature rises under transient load conditions. A method also had to be worked out to simulate the effects of no-load losses that do not exist when the short-circuit method is used to perform thermal tests. Because the temperature rise at any time in the transient load cycle is dependent on the preceding temperatures, a procedure had to be developed to determine a typical starting temperature.

B.4.3 Winding temperature rises during transient loading conditions

Because discontinuing the load at intervals to obtain winding resistances would create periods of no load (significantly reducing the total energy input), would disrupt the thermal cycle, and essentially would make the end point results useless, it was decided that the winding resistance measurements should be made only after the final test interval. The equations of the loading guides would be used to predict the time when the maximum temperature would occur so that the load could be removed and winding resistances taken at that time. A sample calculation describing the procedure to determine when the hottest spot would occur is given in Annex C of IEEE Std C57.115-1991™.

[12]See Annex A, Equation (A.2).

Top oil temperatures and tank surface temperatures were selected to monitor the thermal cycle test because these are the only temperatures convenient to measure unless direct reading hottest spot measuring devices have been installed. Winding temperatures should be estimated periodically, using the relationships between top oil temperature rise and winding temperature rise determined in Clause 9 of this procedure, to assure that excessive winding temperatures do not occur. When hottest spot devices are installed, they should be monitored to assure temperatures do not reach excessive values.

B.4.4 Winding hottest spot temperature determination

As previously discussed, there are no standard procedures for determining the location of the hottest spot nor standard methods for measuring the hottest spot temperature of an energized transformer. Consequently, the hottest spot temperature may be determined by any of the alternatives discussed in 9.8.3.

B.4.5 No-load loss simulation

When using the standard short-circuit thermal test method, no-load losses are not present. The standard procedure simulates the no-load loss by increasing the load during the test so that the load losses generated during the test are equal to the total rated losses (rated load plus rated no-load losses). During a standard temperature rise test, the additional load loss required to simulate the no-load loss may be determined because the final steady state temperatures can be estimated with sufficient accuracy. However, during a temperature rise test under changing loading conditions, the winding resistance changes throughout the test, making it difficult to simulate a constant loss equivalent to the no-load loss. The simulation of a constant loss requires the additional load be continuously recalculated as the winding temperature changes and the total load adjusted accordingly. In this test procedure, a chart (Figure 2) was developed to determine the additional load current required during the performance of the tests.

B.4.6 Initial test conditions

In accordance with the loading guides, the winding hottest spot temperature θ_H can be calculated for the end of any time period during a transient loading cycle by iterating through the cycle using Equation (A.2) through Equation (A.4) for each time period during the cycle. These equations show that the hottest spot at the end of any time period is dependent on the initial top oil temperature at the start of that period. Therefore, in order to determine the temperature at the end of a load cycle by test, it is important that the initial top oil temperature at the start of that test be correct. It should represent the temperature that would be obtained if the load cycle was repeated many times until the temperature cycle became a stable cycle.

Iterative calculations of top oil temperature, performed using a typical load cycle through a number of cycles until the top oil temperatures became stable, were compared with the ultimate top oil temperature calculated due to a conditioning load determined per 10.4. The results of the two calculations procedures compared within approximately 1 °C; therefore, the simpler calculation procedure was chosen for this test procedure.

B.5 Simplified test procedure to simulate a load cycle

Clause 11 is an integrated test procedure that may be used for those cases in which the user’s particular load cycle can be represented by an equivalent cycle consisting of three loads. By using three particular loads representative of the load cycle, rather than the 70%, 100%, and 125% used in Clause 9, the procedures of Clause 9 and Clause 10 may be combined into three tests to obtain the thermal exponents, time constants, and measured winding rises at the end of the equivalent cycle. This has the advantage of reducing the amount of test time required for tests in both Clause 9 and Clause 10.

Annex C

(informative)

Hottest spot measurements using direct reading fiber optics temperature measurements

C.1 Background

Fiber optic temperature measurement devices have proven to be a viable method of measuring the temperature of transformer winding conductors and insulation without compromising the dielectric strength of a winding. The fiber optic sensors, used in the fiber optic temperature measurement devices, have characteristics that make it necessary to observe certain precautions during the location and installation, to assure that satisfactory results will be obtained. The location of fiber optic sensors depends on the method of placement, winding construction, and internal transformer layout.

C.2 Location of sensors

Two precautions should be observed when locating and installing fiber optic sensors. First, the sensors should be located in one or more positions that previous experience or thermal analysis has indicated to be the hottest spot of the transformer. Second, fiber optic sensors should be located such that they are isolated from potential sources of physical damage. On three-phase units, the highest temperature is likely to occur near the top of the center coil. When the transformer is equipped with a load tap changer (LTC), it is recommended the fibers be located to minimize interference between fibers and LTC leads. It is also recommended the fibers be located away from the current transformer leads.

C.3 Sensor placement

Sensors should be placed against an accessible individual strand of conductor in a disk, layer, or helical winding, where the strand can be reinsulated after placement of the sensor. The sensor should be placed alongside of the conductor, in a position where it cannot be accidentally crushed by an adjacent conductor. If a disk, layer, helical, or pancake winding is built with machine transposed cable (MTC), one suggested method of placement is to locate the sensor in the small space that exists at the transposition. Access to the MTC conductor may be obtained by removal of the outer layer of paper. After installation of the sensors, the conductors shall be reinsulated to restore the dielectric strength.

The location of the conductor hottest spot may be at the interface between a conductor and a radial spacer. If so, the sensors may be imbedded in a radial spacer adjacent to the conductor hottest spot. Proper installation in a spacer provides convenient, secured placement, which provides protection from crushing of the fiber optic sensors. Spacers are typically prepared in advance. Sensors should be placed in drilled holes in the spacer, and then cemented in place with a thermosetting resin, which is forced in via a second hole to completely fill any remaining voids in the spacer. Recently, an experimental, soft, expandable spacer has been developed for use in retrofit situations.

C.4 Installation considerations

Generally, fiber optic cable should be treated in the same manner as any other insulating material. Cables should be routed to follow the equipotential lines of the dielectric field. Assemblers should be trained in the proper handling of the fibers to prevent accidental breakage, as the cost to replace fiber optic cables is high.

Three individual lengths of fiber are recommended to connect the sensor to the recording instrument. One fiber optic cable connects the sensor to the exterior of the winding. Another, forming an extension, preferably protected by a large diameter hard insulating tube, runs from the winding to the tank wall. A third extension runs from the outer tank wall to the recording instrument. Fiber optic cables located under oil are connected by an injection molded connector.

Annex D

(informative)

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